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Title: Towards more effective strategies to reduce property level flood risk: standardising the use of Unmanned Aerial Vehicles.

Short title: Reducing property level flood risk

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Abstract: Effective flood risk management strategies require a detailed understanding of the source, extent and impact of flooding. Unmanned Aerial Vehicles (UAVs) enable detailed and accurate data collection that can be used to determine flood source, extent, impact and the presence of property level flood resistance measures. This paper draws on the practical experience of the authors including the use of UAVs during flood events. We highlight the potential uses of UAVs in flood risk management activities and the associated challenges. The impact of a flooding event will also be dependent on how well an area is prepared in terms of community and property level resistance and resilience measures. We have looked at potential reasons why there is not a greater uptake of property level resistance and resilience measures. It is clear that a standardised approach is required if UAVs are to fulfil their potential within flood risk management activities. We have identified five pillars of standardisation that underpin an overarching, purpose driven, cost effective systems-based approach to the use of UAVs in flood risk management. These are: (P1) deployment, data collection and flight related regulatory requirements; (P2) data processing, data merging and outputs; (P3) the introduction and use of innovative approaches and technological integration; (P4) use of outputs for public engagement and; (P5) policy development and governance. We consider that the proposed approach will maximise cost effective information gathering, standardise the way processed outcomes are generated and provide the basis for comparable and robust flood risk information that is based on a single coherent methodology.

Keywords: flood management, statistics, decision–making theory, risk, resilience, pillars, standardisation, data collection, data processing, technological integration, outcomes, policy and governance.

Highlights:

- The lack of coordinated and purpose led approaches results in duplicated data collection efforts and missed opportunities to collect data that could better inform flood risk management activities.
- Unmanned Aerial Vehicles (UAVs) are a useful but underutilised tool within flood risk management activities.
- There is a need to understand and overcome the blockers to the uptake of innovative and disruptive technologies.
- There is a clear need for greater standardisation in the way that flood risk management data is collected and analysed – we propose five pillars of standardisation within an overarching systems based approach.

A standardised approach could help generate greater trust in the interpretation and use of data and would reduce the data collection and processing costs.

The five pillars underpinning purpose driven flood risk management approaches

Given the likely increase of impacts from extreme events on urban settlements across England, driven by changes in land use and underlying climate change trends, there is a clear need to draw together the findings from a range of research outputs and innovative technical, behavioural and engagement approaches to inform the delivery of the flood risk and environmental management strategies in England as outlined in the 25 Year Environment Plan (UK Government, 2018a) and the National Flood and Coastal Erosion Risk Management Strategy for England 2020 (UK Government, 2018b). This requires the development of a multidisciplinary (Fu *et al.*, 2020), integrated and systems based approach (The Institution of Environmental Sciences, 2019) including topics areas such as risk and decision making; public engagement; data acquisition, data analysis and assessment; technical developments and the introduction and implementation of innovative technologies; and economics; policy, regulatory and governance approaches. A system based approach (e.g., Figure 1) will enable their exploration in a collaborative way to understand better the limitations, barriers, drivers of change and interactions across multiple spatio-temporal scales (The Institution of Environmental Sciences, 2019). Such an approach recognises that environmental systems are complex and integrated through interconnected and nested sub-systems referred to in the following discussion as Pillars. The use of Unmanned Aerial Vehicles (UAVs) technology in flood risk management activities can be used to test out the overall approach and to determine whether there are generic lessons that can be applied to other situations. UAVs, commonly known as drones, are small aircrafts piloted by remote control or onboard computers. Within the context of flood risk management, they have been used to capture high resolution data to quantify flood extent and impacts.

A balance has to be struck between continuing technological advances and the development of agreed methodologies that then enable data to be shared and used widely irrespective of who has collected the data or even for what purpose. To that end we have defined five Pillars (P) of standardisation (Figure 1) as follows: (P1) deployment, data collection and flight related regulatory requirements; (P2) data processing, data merging and outputs; (P3) the introduction and use of innovative approaches and technological integration; (P4) use of outputs for public engagement and; (P5) policy development and governance.

There is a need (P1) for the development of a standardised monitoring protocol for all the variables that inform data collection, such as flight altitude, resolution and accuracy of the imagery collected, number and location of waypoints, as well as spatial and temporal survey coverage, amongst others. This should include standards defining a purpose driven use of UAVs to maximise information gathering for flood management decisions pre-, during and post-event and the platforms and sensors recommended for each application.

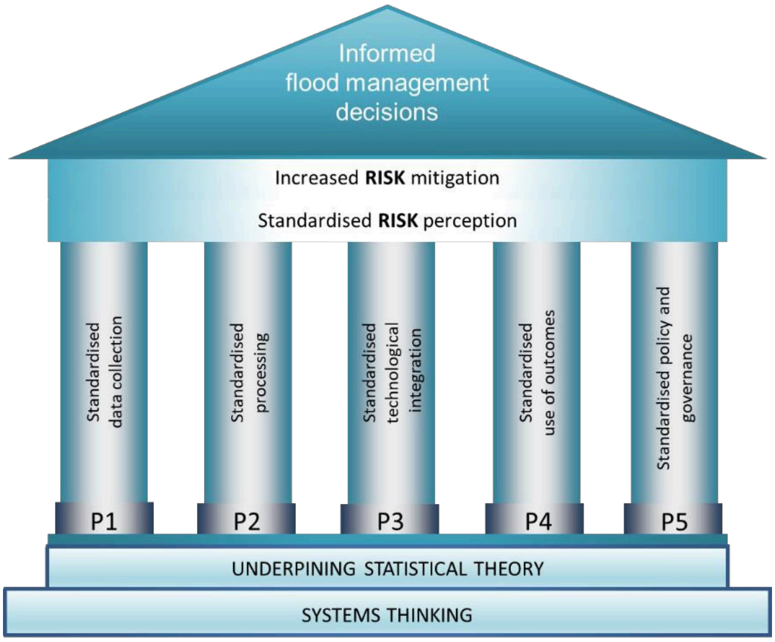

Figure 1. The five pillars (P) contributing towards improved communication strategies, standardised risk perception, data democratisation (Open Flood Data) and more informed flood risk management decisions.

There is also a need to identify flight related regulatory constraints and then propose policy and regulatory changes to address them. In the last few years, there has been a strong push to integrate airspace regulation with UAV operation following the decision of the European Council December 2013 to ensure the progressive integration of UAVs (<7kg) into airspace as from 2016. The regulatory framework developed by the CAA and summarised in CAP722 and CAP393 positions the UK as a leading country in the areas of UAV deployment and operation with its aim being to enable the full and safe integration of all UAV operations in to the UK's total aviation system. The regulations restrict operations over congested areas and near (<50m) people, buildings, vehicles (including vessels) or structures. Although special licenses can be granted to overcome these restrictions, this capability has not yet been explored in full within the context of flood extent and damage assessment.

In addition to the need for a standardised approach to data collection (P1) there is a need for an agreed protocol for data processing (P2). This should focus on the tools (e.g., software) used, the selection of approved and trustable processing algorithms, specific uncertainty and accuracy thresholds and workflow repeatability.

There is often resistance to the introduction and use of innovative and disruptive approaches. Sometimes this can be because policy and regulations are based on the outputs from an existing technique. There is also the time and cost associated with demonstrating equivalence and overcoming the barrier of acceptance by the practioners and decision makers who have always used the traditional approach. Means of overcoming these barriers and blockers need to be found (P3) demonstrating how UAVs can be used in a proactive and purpose driven way to deliver clear benefits over the existing approaches.

The actions outlined above will provide the basis for preparing shareable, comparable and robust flood risk information that is based on a coherent methodology. Means by which such information can inform and facilitate the work of flood risk management practitioners and how they can be used to communicate more effectively with decision makers and the public about the flood risks and mitigation approaches need to be developed (P4). The outputs can also be used to explain more clearly accountabilities and responsibilities including actions to reduce flood risk. This could help inform the decisions made by property owners regarding the measures they can take to reduce their own risks.

There is a need for greater coordination of UAV flights during and after events (P5). This would reduce costs and also provide clarity on why flights are being made. A distinction may need to be made between flights that are for visual observation or news purposes and those where the data has been collected in accordance with an agreed protocol that enables robust data analysis to be carried out. It would be good to be able to access all the UAV data that is being collected before, during and after an event. There would be real benefit in having a single curated source of flood data, collected to agreed standards that can be interrogated and used by anyone.

A shared and easily accessible platform that promotes standardised UAV processed outputs to inform management decisions would reduce overall costs and generate greater trust in the interpretation and use of the data. It would enable informed local, regional and national discussions to be had in relation to the levels of risk experienced in different locations, the actions being taken to mitigate the risks and who should be acting to reduce residual risks. This would include the actions individual householders can take by introducing property level resistance and resilience measures to reduce their risks.

It would also facilitate discussions on: who should fund flood risk reduction; whether the flood risk associated with individual properties (from all sources) should be publicly available; how the funding of flood risk management schemes could be made more transparent; the role of insurance policies and whether premiums should be reduced if individuals introduce property level flood resistance and resilience measures.

Such discussions will need to be tailored to take account of particular flood risk circumstances including those properties: for which it is not cost effective to build community level flood risk management assets; that have recently experienced a flood event and the owners are considering whether or not to include resistance and resilience measures in the repairs and rebuilding work; at high risk of flooding but have not flooded in recent memory. Some property owners do not want to highlight that their properties are at any risk of flooding as this may have a negative impact on the value.

There will be particular challenges where properties are at risk from surface water rather than fluvial or coastal sources. Surface water is not yet as well understood as river flooding and the responsibilities and accountabilities are more widely spread amongst many local councils. Some of the local councils do not have the necessary skills, experience and resources to address the risk.

Challenges for effective implementation of the five pillars of standardisation

A wide range of challenges will curtail the implementation of the five pillars of standardisation. P1 (data collection) will be resource intensive as it will require (i) substantial research on the role that different monitoring parameters play in data collection and (ii) significant computational efforts to optimise UAV surveys pre-, during and post-event. Uptake of the standards will be phased and dependent on the organisations commissioning the survey work requiring their adoption. The potential reduction in the number of suppliers able to meet these standards could result in an increase in the cost of UAV missions. The time required to implement airspace regulatory changes under P1 (data collection) may prolong the time taken to achieve standardisation as national regulations in England are expected to mirror European (EASA) airspace legislation. A potential way to overcome delays in this context could be to grant regulatory exemptions for UAV missions carried out for flood risk management purposes.

The use of a wide range of processing techniques (e.g., machine learning algorithms, photogrammetry) and both commercial and open source software (e.g., TensorFLow, PhotScan, Pix4D, Erdas, Ecognition) has implications for the standardisation of processing techniques (P2-processing). Perhaps the most important challenge within this pillar is the characterisation of the uncertainty associated with different processing techniques and software. Limiting the use of products and techniques to a narrow range could have detrimental consequences for the application of further technological developments. From a systems engineering perspective, a wider range of processing possibilities is preferable; uncertainty estimation and error propagation analysis will facilitate that approach. In turn, this will require additional efforts to address the challenges presented under P3 (technological integration).

The pace at which technological changes are occurring is unprecedented; a robust approach to standardisation (P1- data collection; P2-processing) and integration (P3-technological integration) will depend upon iterative system engineering approaches that rapidly highlight strategies for technological uptake, social acceptance and adaption. Such approaches may be time consuming and will require dedicated resource within government departments and the associated arms-length bodies on their successful implementation via policy, guidelines and regulations as appropriate.

The challenges identified here are not insurmountable impediments to the development and implementation of the five pillars system engineering approach. On the contrary, the beneficial outcomes that can be achieved highlight the need for the standardisation across the multiple overarching domains identified. We illustrate and justify the need for the five pillars of standardisation in the following sections. Much of our work and thinking has been facilitated by the development and deployment of Unmanned Aerial Vehicles (UAVs) over recent years in various aspects of flood risk management activities including flood modelling, flood extent and impacts assessment and during the emergency response.

The benefits of UAVs

UAVs enable detailed and accurate data to be collected more readily than was previously possible. For example current methods used to assess flood extent and impact tend to rely on satellite or aircraft imagery that often fail to provide sufficiently detailed information for that purpose (Cihlar, 1997; Vant-Hull *et al.*, 2007; Sghaier *et al.*, 2018). UAV aerial imagery can overcome these limitations by providing both timely (on-demand) and increasingly detailed (higher resolution) information than can be achieved using satellites or aircraft (Muthusamy *et al.*, 2019).

UAVs can be deployed as and when required subject to favourable weather conditions. Their deployment is fast, simple and cost-effective when compared to other methods such as aircraft (Zhang and Kovacs, 2012). They can fly and collect information under low-cloud cover, which is often present during and immediately after flood events, and enable data capture at higher resolutions than aircraft or satellite can typically provide. Both bespoke and off-the-shelf platforms enable the integration of a varied range of sensors of use in flood risk management activities, from RGB and thermal cameras to sound alarms.

However, there are limitations that still constrain the use of the technology in certain conditions. UAVs are not stable during very windy and wet conditions. Although UAV performance in such conditions has improved in recent years, it still requires substantial enhancement. Commercial platforms include a set of failsafe options that ensure the recovery of the UAV in emergency situations. Obstacle avoidance systems to avoid features when in flight are currently being developed and integrated into new releases of existing platforms.

Compliance with national and international airspace regulation is a mandatory requirement and limits the extent of a flight within the visual line of sight (<500 m from the pilot in command) and less than 400 ft (120 m) above the surface. UAVs cannot fly over congested areas or within 50 m of a person, vehicle or building not under the pilot's control. In addition, the imagery gathered should not break privacy law. Exemptions from the Air Navigation Order can be obtained to overcome some of these regulatory restrictions. For example, on occasions an exemption to fly Beyond the Visual Line of Sight (BVLO) can be obtained to enable UAVs to be flown beyond the 500 m regulatory distance.

Battery endurance is generally a limiting factor with the average time for a single mission depending upon the platform, ranging between 20 and 50 minutes. The selection of a specific UAV platform depends on the characteristics of the mission (e.g., area to be covered, flight plan and deployment logistics) and the data required (e.g., sensor requirements). Fixed wing platforms enable wide area surveying whereas vertical take-off and landing platforms provide high resolution imagery resulting from their hovering capabilities (Zhang and Kovacs, 2012).

The collection of accurate and robust flood extent and impact data also requires careful planning of the logistics around technology deployment and consideration of the data post-processing methods (P1- data collection; P2-processing). Logistics planning is usually overlooked and understudied (Salmoral *et al.*, 2020). In many instances, UAVs are used within flood risk management activities on an ad-hoc, rather than a purpose driven, basis. To the authors' knowledge, the work by Salmoral et al. (Salmoral *et al.*, 2020) is the only comprehensive effort to date that has explored the deployment of UAVs within flood risk management activities including emergency response. Similar efforts to collate information about the use of UAVs uses within the specific context of asset management have been carried out by other authors (Carlisle, Hagstrom and Browne, 2019). Salmoral et al. (Salmoral *et al.*, 2020) identified catchment flood response time (slow, medium, fast) and the time when flood risk management activities are carried out (pre-, during-, post-event) as key drivers in UAV technology deployment (Figure 2). Their work also identified the purpose for which the data should be collected based on the criteria listed above. The proposed framework highlighted the appropriateness of the technology for the collection of specific data to inform flood risk management activities in England and India. The findings highlighted that the deployment of UAVs for flood risk management activities in both countries to date is not coordinated, lacks a structured approach to determining how best to use and deploy UAVs and is not purpose driven (Salmoral *et al.*, 2020). The lack of a coordinated and purpose led response (P5- policy and governance) results in duplicated effort, missed opportunities to collect data that could better inform various aspects of flood risk management activities and the response to that particular event.

The lack of clear protocols detailing how data should be collected (e.g., flight plan and altitude, number of ground control points and imagery overlap) (P1- data collection) restricts the potential to standardise processed outcomes, which in turn limits the ability to compare and share such products widely and constrains how the data can be best used to inform future flood risk management interventions (Salmoral *et al.*, 2020). The situation is further exacerbated by the lack of a coordinated response (P5- policy and governance) to the use of UAVs within a particular flood event with multiple UAV providers flying different missions in an event with a wide range of UAV platforms and sensors.

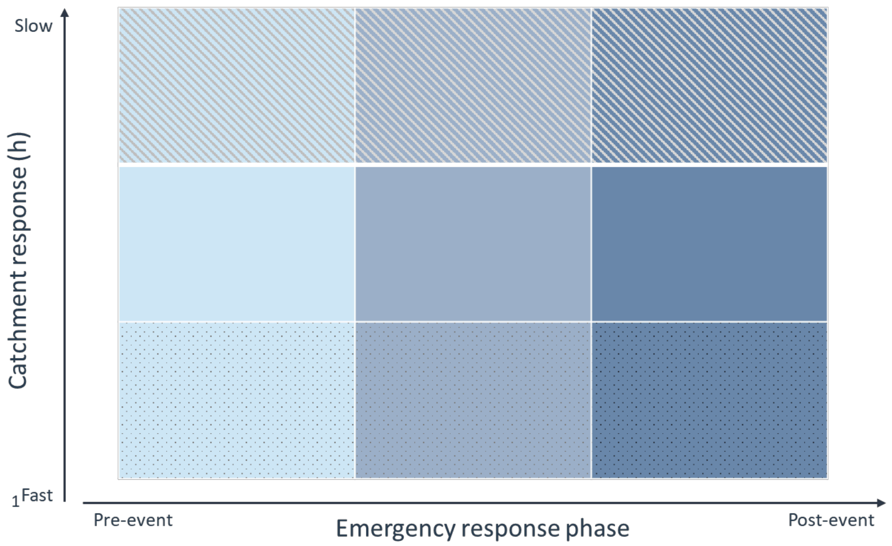

Figure 2. Logistic decision framework for the deployment of UAVs for flood emergency response. Adapted from (Salmoral *et al.*, 2020). *Catchment response refers to the time between the start of a rainfall event and the potential for the flooding of properties (slow >8h; medium 3h to 8 h; fast <3h). Emergency flood response represents the time when flood management activities are carried out (pre-, during- and post-flood event).*

Data post processing methods have advanced significantly in the last couple of decades, from photogrammetric analysis of high resolution RGB imagery from UAVs to the development of machine learning techniques and systems-of-systems models for data analysis and interpretation (Joannou *et al.*, 2019; Saravi *et al.*, 2019). Standardised monitoring protocols (P1- data collection) that take into account the purpose for which the data is being collected and the associated post processing workflow (P2-processing) will reduce the uncertainty and increase the reliability of any outcomes generated. In the specific case of UAV data collection, such protocols need to embrace a wide range of considerations, including but not limited to, post-processing algorithms and models used, outcome replicability, outcome accuracy and permissible uncertainty (bias and precision) thresholds. Following the approach by Salmoral et al. (Salmoral *et al.*, 2020), standardised monitoring protocols (Figure 2) could be used to inform how data should be collected for each of the plausible combinations of catchment response time and flood risk management activity.

Effective flood risk management

Previous research carried out for the case study area of Cockermouth (Cumbria, UK) highlighted the importance of understanding the source, extent and impact of flooding if appropriate flood risk management practices are to be developed and implemented (Cabinet Office, 2008; UK Government, 2010). Also how well an area is prepared in terms of community and property level resistance and resilience measures (Bonfield, 2016).

Cockermouth (Cumbria, UK) experienced serious flood events in 2005, 2009 and 2015 (Marsh *et al.*, 2016). In 2015, the town was severely affected by storms Desmond (5-6/12/2015), Eva (24/12/2015) and Frank (29-30/12/2015) (Marsh *et al.*, 2016; Mett Office, 2020). Storm Desmond resulted in intense and persistent rainfall. In the northern Pennines record-breaking rainfalls amounts of 179 mm over 36 hours, 341.4 mm over 24 hours and 405 mm over 24 hours were recorded at Garrigill Noonstones Hill, Honister Pass and

Thirlmere, respectively (Marsh *et al.*, 2016). Storm Desmond resulted in severe flooding with 5,200 homes in the northeast of England being impacted (Mett Office, 2020). Carlisle reported 1,930 properties being affected by flooding whilst 2,140 were reported in Kendal. In Lancaster, thousands of properties lost power for a number of days (Marsh *et al.*, 2016).

Following the flooding of Cockermouth in 2009 and 2015, and in other areas, questions were raised about the utility of the available flood risk maps (P1- data collection; P2- processing), the underpinning flood models (P2- processing) and the associated flood warning systems (P4- use of outcomes; P5- policy and governance) (Zurich, 2015). In Cockermouth for example, a number of properties were flooded that were not expected to, based on the flood risk maps (Rivas Casado *et al.*, 2018; Muthusamy *et al.*, 2019). The flood models and maps for Cockermouth were for fluvial flooding. The available flood models were investigated further to see if they could be refined (P2- processing) to align better with the flooding observed. However, when we assessed the intensity of the 2015 rainfall event, the flooding extent and the locations of the affected properties, we decided to examine whether surface water (pluvial) (P1- data collection; P2 -processing) flooding could be making a significant contribution to the observed impact (Muthusamy *et al.*, 2019). A digital terrain model (DTM) and a digital surface model (DSM) obtained from the Environment Agency (EA) were used to generate a high resolution digital elevation model (DEM) of the area (Muthusamy *et al.*, 2019). The DEM was used to generate a 2D flood model in HEC-RAS (v5) 2D and to carry out flooding simulations with and without surface water flooding. The number of residential properties affected by flooding was validated using a combination of modelled results and high resolution RGB UAV imagery specifically collected for that purpose. To the authors' knowledge, this was the first attempt to combine remote sensing data, hydrological modelling and flood damage data at a property level to quantify the extent of flooding and damage caused by fluvial and surface water flooding in the same event (P2- processing). The results (Figure 3) we obtained clearly demonstrated that the contribution of surface water flooding was significant for the case study area and it should not be ignored. Data collection protocols (P1- data collection) should therefore take into account fluvial flooding to robustly inform flood management decisions. For this event the flood depths from surface water flooding were lower than those observed for fluvial flooding. However, the area affected by surface water flooding was significant and resulted in additional properties being flooded. Surface water flooding increased the overall number of affected properties by 25% (51 houses). It also increased the flood depths for some properties affected by fluvial flooding by more than 50% (Muthusamy *et al.*, 2019). The economic impact from surface water flooding as a consequence of the 2015 flood event was estimated to be £4.8 million whilst that from the fluvial and the combined (fluvial and surface water) flooding was estimated to be £10 million (Rivas Casado *et al.*, 2018).

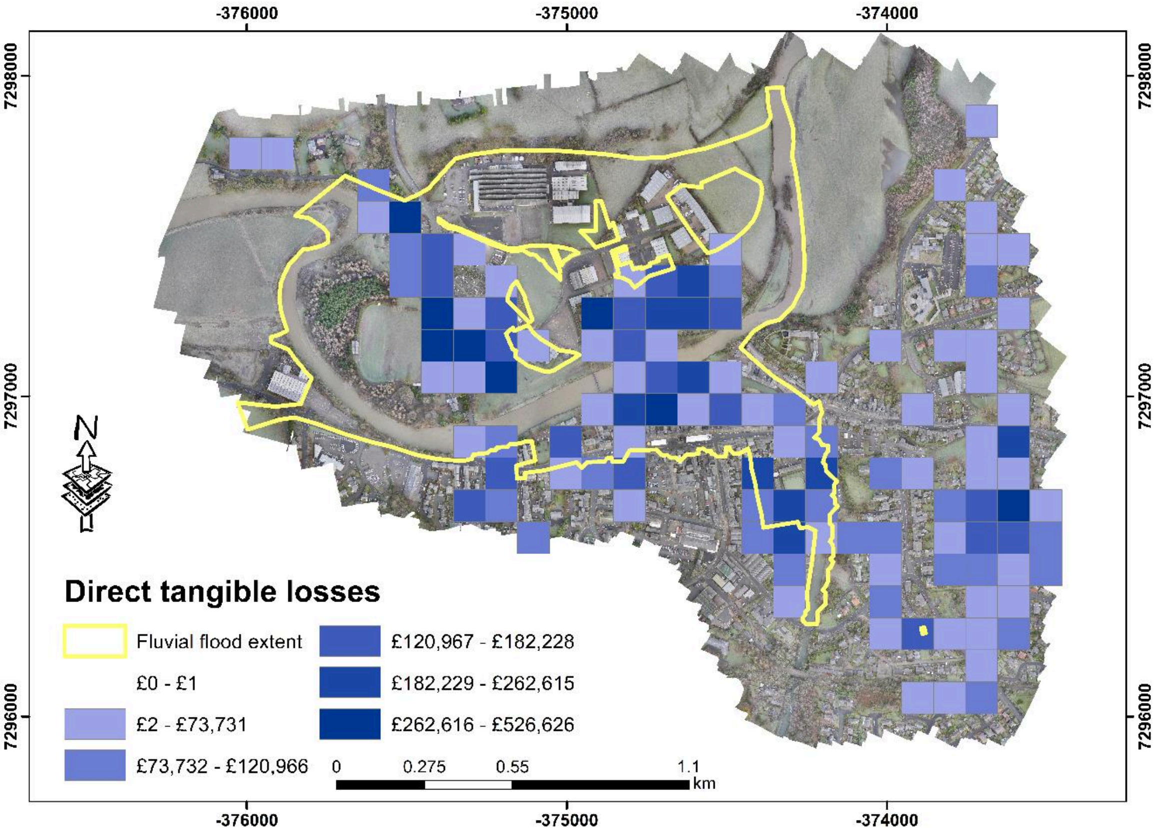

Figure 3. Direct tangible losses associated with fluvial and surface water flooding. Fluvial flooding occurs within the fluvial flood extent (yellow polygon) whereas surface water flooding occurs outside the flood extent. Adapted from (Rivas Casado *et al.*, 2018).

These findings show the importance of taking surface water flooding into consideration in flood risk management assessments and in the responses to flood events. Understanding about surface water flooding and the associated information and risk management strategies are being developed but are less well-defined than those in place for fluvial flooding (Environment Agency, 2019). Fluvial flooding from main rivers in England is the responsibility of the Environment Agency. Addressing the risks associated with surface water flooding is the responsibility of unitary authorities and county councils (i.e., Lead Local Flood Authorities). For a number of councils this is a challenge as they do not have the technical skills or resources to deal with the risks arising from surface water flooding. Surface water flooding risks are also likely to increase with increasing urban development and climate change. In addition, the risks associated with surface water flooding, and as it is sometimes known flash flooding, can be more difficult to communicate effectively (P4- use of outcomes) than those for fluvial flooding.

We also used the Cockermouth 2015 flood data to estimate the direct tangible losses to residential property owners (Rivas Casado *et al.*, 2018) (P2- processing; P4- use of outcomes; P5- policy and governance). An important aspect of the emergency response to a significant flood event is to assess the extent and impact of the flooding including on individual properties (Bonfield, 2016). For example, is it the roads and gardens that have flooded or has the water entered the living areas of the properties. It is also important to understand if properties have property level resistance measures and whether these are functioning properly (Bonfield, 2016). This helps inform the emergency response operations and the subsequent recovery activities including those of the insurance industry in terms of dealing with insured losses and facilitating payments to policy holders so that they can commission the necessary repairs and rebuilding works.

The high resolution RGB UAV aerial imagery was captured after the flood event (P1- data collection) and analysed visually to identify proxy variables (e.g., scour, household waste) indicative of internal property flooding (P2- data processing). The information was then used to identify residential properties affected by flooding (Rivas Casado *et al.*, 2018). When combined with loss adjustment models, the data enabled an estimation of the damage caused by the flood to individual residential properties without the need to access the area. The accuracy (P1- data collection) of the data collected in terms of (i) location of each property and (ii) estimate of the damage caused facilitated the rapid estimation of the losses to residential properties. Figure 3 shows the direct tangible losses estimated for the flooded residential properties; flood impact has been presented on a 100 m x 100 m grid cell to anonymise damage to individual properties. Some of the cells indicate economic damages of up to £526k Direct tangible losses were estimated based on property type and age (e.g., pre-1919 detached, 1975-1985 semi-detached, and 1919-1944 flat) at 2016/17 prices and based on the water depth within the property. The losses were estimated without VAT or other indirect taxes. The methodology by Penning-Rowsell *et al.* (Penning-Rowsell *et al.*, 2013, 2016) was followed at all times (P2- processing).

Typically flood risk, for mapping and insurance purposes, tends to be assessed at a post code level (WSP, 2019). Data is rarely available that enables a property level risk assessment to be carried out. Yet it is known that individual property level features such as the immediate topography, or the height of the door threshold in relation to the surrounding ground or the presence of property level resistance and resilience measures can all have a major influence on the impact suffered. This can give rise to significantly different impacts and property owner experiences within the same flood event for properties within one postcode.

The data we collected enabled the influence of micro-topography at a property level to be evaluated (P1- data collection). The importance of microtopography (Thompson, Katul and Porporato, 2010) in flood management has been recognised by multiple authors as a key factor in identifying flood impact (Schumann, Muhlhausen and Andreadis, 2019); buildings, wallsand local gradients, are important considerations when determining the impact of of localized flow conditions and of flood impacts at a local level (Mason *et al.*, 2003).The DSMs obtained from UAVs by means of photogrammetry can achieve an RMSE of ground levels and the heights of other features of around 3 cm (Forlani *et al.*, 2018). The increased resolution of UAV derived geomatic products compared with more traditional remote sensing methodstherefore enables the generation of DEMs and DSMs that provide information about the microtopography of urban areas in flood prone zones (P2- data processing). High resolution DEMs provide more accurate and better defined flood maps (Ogania *et al.*, 2019) which in turn provide more robust estimates of the areas affected by flood events. They also provide accurate information on property level flood protection features such as raised doorsteps, as well as, local slope gradients and orientations. In many cases such features can be the difference between water entering the property or not. Note that high resolution geomatic products are generally obtained via surveys conducted pre- and post-event, when the area of interest is not flooded. This in turn enables the ground control points to be positioned prior to UAV deployment resulting in more accurate geolocation. Previous authors have demonstrated that as few as 1 ground control point every 2 hectares provide DEM accuracies suitable for flood risk modelling (Coveney and Roberts, 2017).

The research outcomes summarised above help meet some of the gaps in knowledge that currently exist around P1-P5. Further research is required to increase the baseline of evidence required to set standardised protocols for each of the pillars for their adoption at a national level.

Flood risk perception and the uptake of property level protection measures

There is a wide range of property and community level resistance and resilience measures available that can minimise the impact of flooding on residential properties and speed up the recovery phase (Oakley *et al.*, 2020). However, in England the uptake of such measures by property owners is still relatively low (Kreibich *et al.*, 2005; Bichard and Kazmierczak, 2012; Bubeck, Botzen and Aerts, 2012; Kellens, Terpstra and De Maeyer, 2013; Terpstra and Lindell, 2013; Joseph, Proverbs and Lamond, 2015) as was clear in the Cockermouth studies. The drivers underpinning this behaviour are complex and varied and are usually explained by means of Protection Motivation Theory (PMT), a widely used model to characterise consumer choices (Oakley *et al.*, 2020).

Recent research by Oakley et al (Oakley *et al.*, 2020) suggests that this theoretical framework could be improved by taking into account multiple sources of decision bias, namely: availability, optimism, myopia, loss aversion, emotions and complexity. Overall, decision bias significantly conditions the way flood risk is perceived by individuals and actions are taken to implement flood protection measures. For example, availability bias refers to the ease by which specific risks come to mind; clear risks (shark attack) are overestimated whereas those risks that are not properly understood (flooding) are underestimated. Optimism bias captures the predisposition of people to believe they are more likely to be affected by positive events and are at lower risk than other people to have a negative experience. Myopia explains the inclination of people to prioritise on short time horizons whereas loss aversion covers the predilection of people for gains over losses. These sources of bias are influenced by emotions (emotional bias) as people tend to weight decisions based on how they feel about them rather than what they rationally think about them. Finally, complexity bias refers to the increased level of procrastination that can be observed as decisions become more complex (Tversky and Shafir, 1992).

Within the specific context of flooding, these sources of bias interact. An assessment of the biases helps provide a better understanding of why the majority of people do not proactively introduce resistance and resilience measures within their properties. In general people believe it is unlikely their house will be flooded and therefore do not need to take any action to reduce the risk of this happening. Not surprisingly, homeowners that have recently been affected by flooding take the risk of future flood events more seriously than homeowners that live in a high-risk area but have not yet experienced a flood. However, the seriousness with which this risk is perceived, for those who have experienced a flood event, fades with time.

The way that risk is presented and communicated also has an impact on the decision whether or not to put in place property level flood resistance and resilience measures. For example, the use of return periods, such as a flood being a 1 in 100 year frequency event, leads to a lower perception of the risk and a lower uptake of flood protection measures. Similarly, the usual framing of insurance products in which an immediate cost in relation to purchasing a policy is traded for an uncertain longer-term gain discourages uptake of such products (Oakley *et al.*, 2020).

Overall, the communication strategy needs to consider carefully how risk is presented to homeowners and significant effort needs to be invested in explaining the benefits, possible mitigations, the imperative of taking action and the potential emotional and economic costs of not implementing measures (Oakley *et al.*, 2020).

The overall perception of risk is conditioned by all of the factors outlined above which then affects the uptake of property level resistance and resilience measures. These findings (Oakley *et al.*, 2020) were used to develop the Adapted Protection Motivation Theory (Figure 4). This provides a rationale for more structured discussions with potentially affected property owners.

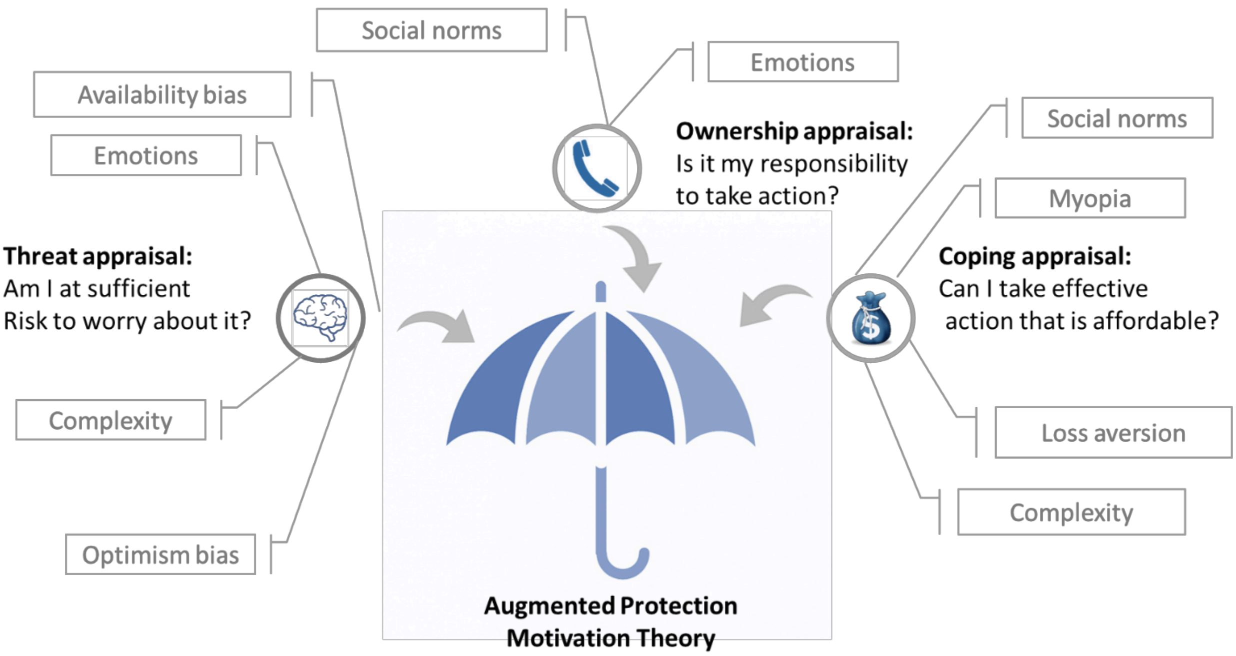

Figure 4. Schematic diagram depicting the Augmented Protection Motivation Theory developed by Oakley et al[]. Adapted from (Oakley *et al.*, 2020).

It is important to address peoples' perceptions so that these can then be answered in a way that enables progress to be made on the introduction of more property level resistance and resilience measures thereby reducing the impact and upset caused by future flooding events.

Such communications also need to be informed by objectively agreed data and information presented in an easily understood way. This will need to take account of all sources of flooding. For example, in Cockermouth both fluvial and surface water flooding needs to be addressed and will require an integrated approach between the different authorities including the EA for fluvial flooding and the local council for surface water flooding.

UAV data derived 3D visualisation techniques that accurately represent the development and impact of a flood event (P2- data processing) can be an important communication tool (Video 1) with those who have been or may be flooded (P5- policy and governance). Such techniques can help people understand the risk that they and their property face and therefore reduce the decision bias associated with risk perception. Such an approach may encourage some individuals to introduce property level flood resistance and resilience measures. Standardised protocols defining how UAV data needs to be processed (P2- data processing) can be used to address peoples' perception of risk and risk management practices and encourage the uptake of property and community level resilient and resistance measures (P5- policy and governance). The Adapted Protection Motivation Theory helps identify the key areas (processed outcomes) within which UAV derived products (e.g., visualisation tools) can be used to address change risk perception and inform policy and regulation. This in turn helps prioritise UAV data collection efforts pre-, during- and post-event. To date UAVs have generally been used within the context of news coverage and flood extent and impact assessment. The use of UAVs to inform risk perception will require a tailored surveying strategy (P1- data collection). The Adapted Protection Motivation Theory could provide the first steps towards defining the logistics (e.g., flight plan, camera configuration) of such UAV missions. In time, this information will be incorporated to the UAV decision matrix outlined in Figure 2.

Video 1. 3D visualisation derived from UAV imagery for the case study area of Cockermouth after a flood event. Available at https://youtu.be/bv3FmIQpW1A .

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